NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WARTIME REPORT

ORIGINALLY ISSUED
October 1945 as
Advance Confidential Report L5H04

COMPARISON OF FIXED-STABILIZER, ADJUSTABLE-STABILIZER AND ALL-MOVABLE HORIZONTAL TAILS

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WASHINGTON

NACA ACR No. L5H04

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SUMMARY

An analysis is presented to compare longitudinal stability and control characteristics obtained with a conventional fixed-stabilizer, an adjustable-stabilizer, and an all-movable horizontal tail. The tail-area requirements, control forces required in the critical landing condition, static margin, control-force gradients in a dive recovery, and elevator-free stability are investigated. The analysis includes a comparison for the various tails of the effect of a partial-wing stall on the control-force gradient in a dive recovery. The effect of an increase in the tail aspect ratio is also investigated.

The results of the analysis indicated that, with regard to requirements for longitudinal static stability and adequate control in landing, the all-movable and adjustable-stabilizer tails can provide, with considerably smaller tail areas, the same range of permissible center-of-gravity positions as the conventional fixed-stabilizer tail.

The comparison of the longitudinal control characteristics on the basis of a specified range of permissible center-of-gravity positions indicated that the adjustable-stabilizer tail allows considerably smaller control balance for the rate of change of hinge-moment coefficient with elevator deflection than the fixed-stabilizer tail. The comparison also indicated that the increase in control-force gradient as a result of a partial-wing stall in a dive recovery will be significantly smaller with the all-movable and adjustable-stabilizer tails than with the conventional fixed-stabilizer tail.

INTRODUCTION

The present trend toward higher speeds and greater size of airplanes is increasing the demands on the horizontal tail with regard to obtaining adequate longitudinal control under some important flight conditions. In particular, the use of flap devices that give increasingly large increments in lift in order to maintain reasonable landing speeds may add appreciably to the diving moments which must be balanced out by the longitudinal control in the three-point-landing attitude. An analysis of a typical fighter airplane (reference 1) shows that a fixed-stabilizer horizontal tail of conventional size would provide markedly inadequate longitudinal control in landing with a full-span slotted or Fowler flap. The results of reference 1 show that with a slotted flap, the airplane would require an increase in tail volume of 56 percent in order to permit a center-of-gravity travel of 6.5 percent of the mean aerodynamic chord and that this 56-percent increase in tail volume would permit a center-of-gravity travel of only 2.1 percent with a Fowler flap. Further, reference 2 has shown that in the case of high-speed pull-outs a large diving moment may occur as a result of a partial-wing stall caused by critical compressibility effects and the inadequacy of the normal elevator for counteracting this diving moment is responsible in many cases for the extreme difficulty recently experienced in recoveries from high-speed dives.

A common method of obtaining greater longitudinal control has been to increase the horizontal-tail volume by increasing the tail area. It is evident, however, that as compared to the conventional horizontal tail having a fixed stabilizer, the adjustable stabilizer and all-movable control permit an increase in the tail effectiveness. The adjustable-stabilizer and all-movable tails therefore should provide a specified degree of longitudinal control with a smaller area than that required with a fixed-stabilizer tail. A comparison of the different types of horizontal tail on the basis of specified stability and control requirements would serve therefore to indicate the comparative merits of these tails in regard to obtaining improvements in horizontal-tail design.

Results are presented of an analysis in which the conventional fixed-stabilizer, the adjustable-stabilizer, and the all-movable horizontal tails are compared on the basis of tail-area requirements and airplane static longitudinal stability and control characteristics. The analysis is made for these tail configurations on a modern fighter airplane. The data for the horizontal tails are presented, however, for a wide range of stability and control requirements, so that the results of the present investigation can be applied to a number of airplane types. The analysis of the horizontal tails includes a comparison of the longitudinal control characteristics for flight conditions in which the wing is partially stalled. The effect of an increase in the tail aspect ratio on the static longitudinal stability and control characteristics is also considered.

SYMBOLS

c_w mean aerodynamic chord of wing, feet

l_t tail length measured from quarter-chord point of mean aerodynamic chord of wing to quarter-chord point of tail, fraction of c_w (see fig. 1)

l_o distance measured from quarter-chord point of mean aerodynamic chord of wing in original position to neutral point, fraction of c_w; positive when neutral point is behind quarter-chord point (see fig. 1)

l_{cg} distance measured from quarter-chord point of mean aerodynamic chord of wing in original position to center of gravity of airplane, fraction of c_w; positive when center of gravity is behind quarter-chord point (see fig. 1)

Δl_{cg} distance center of gravity is moved, fraction of c_w; positive when moved back, primed to indicate that wing is moved simultaneously

x static margin with elevator fixed (distance measured from airplane center of gravity to neutral point), fraction of c_w; positive when neutral point is behind center of gravity (see fig. 1)

p distance measured from aerodynamic center of all-movable tail to pivot of main surface, feet; positive when pivot is behind aerodynamic center

Δl_w distance wing is moved, fraction of c_w; positive when wing is moved back, primed to indicate that center of gravity is moved simultaneously

Δl_o change in neutral-point position due to change in horizontal-tail area, fraction of c_w

Δl_{o_F} change in neutral-point position due to freeing the elevator control, fraction of c_w

$(\Delta l_o)_{st}$ change in neutral-point position that results from partial-wing stall, fraction of c_w

Δd_{st} rearward movement of aerodynamic center of wing that results from a partial-wing stall, fraction of c_w

c chord, feet

$\bar{c}_t$ root-mean-square tail chord, feet

$\bar{c}_e$ root-mean-square elevator chord, feet

b span (of wing unless otherwise indicated), feet

S area (of wing unless otherwise indicated), square feet

ΔS_t change in tail area S_t required with modified tail to maintain specified static margin

A aspect ratio

r_t taper ratio of tail

W weight of airplane

w_t weight of horizontal tail per unit area, pounds per square foot

W_w total weight of wing, pounds

ρ air density, slugs per cubic foot

K_e elevator gearing ratio, radians per foot stick travel

q dynamic pressure, pounds per square foot

α angle of attack of airplane measured as angle between the thrust axis and wind direction at infinity, degrees; primed to indicate that α is corrected for ground interference effects

δ angular deflection of control surface, degrees

$i_{t_{max}}$ maximum angular deflection of stabilizer measured with reference to thrust axis, degrees

$\delta_{e_{max}}$ maximum negative angular deflection of elevator, degrees

ϵ downwash angle at tail, degrees; primed to indicate that ϵ is corrected for ground interference effects

τ elevator-effectiveness parameter equal to the change in angle of attack of the tail required to give the same total lift over the tail as that contributed by 1° of elevator deflection

a slope of lift-coefficient curve per degree, (for airplane unless indicated otherwise); primed to indicate parameter is corrected for ground effects

$\frac{d\epsilon}{d\alpha}$ rate of change of downwash angle at tail with angle of attack of wing

$\left(\frac{d\epsilon}{d\alpha}\right)_{st}$ rate of change of downwash angle at tail with angle of attack of wing after beginning of wing stall

$\left(\frac{\partial\alpha_t}{\partial\delta_{f_t}}\right)_{c_{l_t}}$ rate of change of angle of attack at section of the tail with tab deflection for constant lift at section

[redacted]

$\left(\frac{\partial c_{m_t}}{\partial \delta_e}\right)_{C_{L_t}}$ rate of change of pitching-moment coefficient of tail about quarter-chord point of tail with elevator deflection for constant lift over tail

$\left(\frac{\partial c_{m_t}}{\partial \delta_{f_t}}\right)_{c_{l_t}}$ rate of change of pitching-moment coefficient about quarter-chord point of section of tail with tab deflection for constant lift at section

C_{L_t} lift coefficient of tail

C_{L_t}' maximum negative lift coefficient of tail that can be obtained in the three-point attitude with ground-effect corrections

$C_{L_{max}}$ maximum lift coefficient of wing with flaps fully deflected

c_{l_t} section lift coefficient of tail

C_m pitching-moment coefficient about center of gravity of airplane $\left(\frac{M}{qSc_w}\right)$

M pitching moment about center of gravity of airplane, foot-pounds

$C_{m_{\delta_e}}$ rate of change of C_m with δ_e

$C_{m_{\alpha_t}}$ rate of change of C_m with α_t

C_h elevator hinge-moment coefficient $\left(\frac{H}{q\bar{c}_e{}^2 b_e}\right)$

H elevator hinge moment, foot-pounds

$C_{h_{\delta_e}}$ rate of change of C_h with δ_e

$C_{h_{\alpha_t}}$ rate of change of C_h with α_t

$\frac{dC_{m_1}}{d\alpha}$ contribution to C_m per unit change in α of combined effects of all factors other than wing and tail

[redacted]

ΔC_{m_2} combined contributions to C_m of factors other than those represented by term $C_{L_{max}} l_{cg}$ and tail

c_{m_t}' contribution to C_m of the tail pitching moment about tail quarter-chord point that results from the maximum negative elevator deflection

$\frac{dc_{m_t}'}{d\delta_e}$ contribution to C_m per unit change in δ_e of the tail pitching moment about tail quarter-chord point

J factor used to determine contribution of tab to tail lift

E' factor used to determine total pitching-moment contribution of tab about quarter-chord point of tail

F_n change in elevator control force per unit change in normal acceleration, pounds per g

g acceleration of gravity, 32.2 feet per second per second

F_L control force required to land at minimum speed with center of gravity in most forward position, pounds

$(\Delta F_n)_{st}$ change in F_n that results from partial-wing stall, pounds per g

B, D constants used to determine F_n

K constant used to determine $(\Delta l_o)_{st}$, $\left(\frac{a_t q_t S_t}{a_w q S}\right)$

Subscripts

t tail

e elevator

st occurs after wing begins to stall

w wing

f_t tab for all-movable tail

METHOD OF ANALYSIS

Basis for Comparison

The fixed-stabilizer, adjustable-stabilizer, and all-movable horizontal tails on a modern fighter airplane are compared in the present analysis. Because the present trend in tail design is toward higher aspect ratios, aspect ratios of 4.24 and 5.82 were treated for the fixed-stabilizer tail in order to give data showing the effects of increases in aspect ratio. The areas required for the three types of tail having equal aspect ratios (5.82) were compared for an equal range of permissible center-of-gravity position. With the respective areas determined in this manner, the three types of tail were also compared on the basis of the following factors:

(1) The effect on the static margin of the airplane of replacing the fixed-stabilizer tail with other tail designs

(2) The control-balance required to obtain a specified control-force gradient and variation of control-force gradient with center-of-gravity position

(3) The effect on static longitudinal stability of freeing the elevator control

(4) The maximum control forces in a three-point landing at minimum speed

(5) The effect of a partial-wing stall on the control-force gradient in a dive recovery

Data for Calculations

The basic data, which are representative of data for a modern fighter airplane, that were used in calculating the stability and control characteristics of the selected airplane are shown in table I.

The basic design data and aerodynamic parameters for the horizontal tails are given in table II. The calculations for the tails were made for a plan form having an aspect ratio of 5.82 and a taper ratio of 2.16, which corresponds to the wing plan form of the airplane. The calculations for the fixed-stabilizer tail were also made for a plan form having an aspect ratio of 4.24 and a taper ratio of 1.71, which corresponds to the plan form of the original tail of the subject airplane.

The stabilizer setting, the ratio of elevator chord to tail chord, and $\delta_{e_{max}}$ for the fixed-stabilizer tail were assumed to be the same as for the original horizontal tail on the subject airplane. For the adjustable-stabilizer tail, the maximum angular travel of the stabilizer was limited by the condition that, with the wing flaps fully deflected at 120 percent of the minimum speed, the negative angle of attack of the tail was about 2.5° below its negative stalling angle. It was further specified that with the stabilizer fully deflected, the airplane could be trimmed at all times in a normal landing maneuver by use of the elevator. In order for the tail to operate within the linear range of the elevator effectiveness, the values for the ratio of the elevator chord to tail chord and for $\delta_{e_{max}}$ were assumed to be smaller for the adjustable-stabilizer tail than for the fixed-stabilizer tail - that is, c_e/c_t was reduced from 0.32 to 0.20 and $\delta_{e_{max}}$ was reduced from -25° to -15°. These assumptions were based on the data of figure 3 of reference 3 and were necessary because of the large increase in the negative incidence of the tail when the stabilizer is fully deflected.

The all-movable horizontal tail considered in the present analysis is similar to the all-movable vertical tail surface reported in references 4 and 5. For this type of tail, the pivot is located at the aerodynamic center of the tail or at some point behind it and a tab, linked to the main surface, moves in the same direction as and in a predetermined ratio to the main surface. The proportions of the tab and the tab-linkage ratio δ_{f_t}/δ_e were so determined that the control-force characteristics for the all-movable horizontal tail, when used on the subject airplane, would be comparable to those obtained with the other types of horizontal tail. The maximum negative deflection of the all-movable tail was so determined that the negative stalling angle for the tail could be obtained in a three-point landing at minimum speed. In contrast with the allowance of 2.5° assumed in the case of the adjustable-stabilizer tail, which was set for the approach condition, no allowance was assumed for the all-movable tail in the landing condition because the adjustable-stabilizer tail was believed to be generally more difficult to unstall than the all-movable tail. The effect of other considerations that may limit the maximum angular travel of the stabilizer and of the all-movable control is discussed herein in the section entitled "Results and Discussion."

The values for the aerodynamic parameters a_t and τ used in the calculations for the horizontal tails were based on the data of reference 3. In the case of an all-movable tail with a tab,

$$\tau = 1 - 0.1J\left(\frac{\partial \alpha_t}{\partial \delta_{f_t}}\right)_{c_{l_t}} \frac{\delta_{f_t}}{\delta_e}$$

where J is a function of the span and location of the tab and of the tail taper ratio. Values for J were obtained from figure 2 of reference 6. The factor 0.1 represents the slope for the section lift curve per degree.

Procedure for Calculations

The symbols that refer to the position of the various points along the longitudinal axis of the airplane are identified in figure 1. The quarter-chord point of the mean aerodynamic wing chord of the subject airplane is taken as the reference chord, and distances along the longitudinal axis are measured in fractions of the mean aerodynamic chord of the wing.

The range of the permissible center-of-gravity positions was limited in the rearward direction by the elevator-fixed neutral point as determined for the cruising condition and in the forward direction by the requirement for adequate control in a three-point landing at minimum speed.

The most rearward position for the center of gravity or the neutral point for the cruising condition with elevator fixed was determined from the equation

$$a_w l_o + \frac{dC_{m_1}}{d\alpha} - \frac{a_t q_t S_t\left(1 - \frac{d\epsilon}{d\alpha}\right)\left(l_t - l_o\right)}{qS} = 0 \qquad (1)$$

where l_o corresponds to the limiting rearward position for the center of gravity. The parameter $d\epsilon/d\alpha$ in equation (1) was evaluated as 0.4 from the data of reference 7. The term $dC_{m_1}/d\alpha$ in equation (1) represents the combined contribution to C_m of factors other than the wing and tail, such as power and fuselage effects. This term was evaluated by means of unpublished flight-test data for the subject airplane from which the position of the neutral point for the cruising condition with elevator fixed was obtained. The solution of equation (1) with the value of l_o obtained from the flight-test data then determines the value for $dC_{m_1}/d\alpha$. The term $dC_{m_1}/d\alpha$ was thus evaluated as 0.01 and was assumed in the computations to be independent of the center-of-gravity position. The differences in the effect of power at cruising speed for the various tails were neglected, so that the value for $dC_{m_1}/d\alpha$ was assumed to be independent of the size and type of horizontal tail.

The most forward center-of-gravity position for a three-point landing at minimum speed was calculated from the formula

$$C_{L_{max}} l_{cg} + \Delta C_{m_2} - \frac{q_t S_t C_{L_t}'\left(l_t - l_{cg}\right)}{qS} + c_{m_t}' = 0 \quad (2)$$

where l_{cg} corresponds to the limiting forward center-of-gravity position. In equation (2), the term ΔC_{m_2} refers to the landing condition and represents the combined contribution to C_m of factors other than the tail and the factor $C_{L_{max}} l_{cg}$. The term was evaluated by means of unpublished flight-test data for the subject airplane from which the most forward permissible center-of-gravity position in landing was obtained. The solution of equation (2) with the value of l_{cg} obtained from the flight-test data then determines the value for ΔC_{m_2}. The term ΔC_{m_2} thus obtained was evaluated as -0.063. This value of ΔC_{m_2} was assumed to be independent of the size and type of tail and also of the center-of-gravity position. The factor C_{L_t}' in equation (2) is the maximum negative tail lift coefficient that can be obtained in the three-point-landing attitude and was determined from the equation

$$C_{L_t}' = a_t'\left(\alpha_t' - \epsilon' + i_{t_{max}} + \tau\delta_{e_{max}}\right) \tag{3}$$

where α_t', a_t', and ϵ' are the values for these parameters in the landing at minimum speed with ground-effect corrections applied in accordance with the method of reference 8. The term c_{m_t}' in equation (2) is the contribution to C_m of the tail pitching moment about the tail quarter-chord point that results from the maximum negative elevator deflection in the landing condition, and

$$c_{m_t}' = \frac{\left(\frac{\partial c_{m_t}}{\partial \delta_e}\right)_{C_{L_t}} \delta_{e_{max}} q_t \bar{c}_t^{\,2} b_t}{qSc_w}$$

The effect on the static margin x of the airplane of replacing the fixed-stabilizer horizontal tail with other tail designs having different tail areas was determined on the basis of the neutral-point positions, which were obtained from equation (1) for a large range of values of S_t/S. The means considered for maintaining a given static margin with a modified tail of different area included an appropriate shift of the center of gravity Δl_{cg} or an appropriate shift of the wing Δl_w. The value of Δl_{cg} is equal to the shift of the neutral-point position associated with the use of the modified tail minus the shift in the center-of-gravity position that results from the change in the tail weight. In the computations for Δl_w, the quarter-chord point of the tail was assumed to be moved an equal distance in the same direction as the wing so that the tail length l_t is unchanged. If the effect on the airplane center of gravity of the wing and tail weights are included, the formulas for Δl_{cg} and Δl_w become

$$\Delta l_{cg} = \Delta l_o - \frac{w_t}{W} l_t \, \Delta S_t \qquad (4)$$

$$\Delta l_w = \frac{-\Delta l_o - \frac{w_t}{W} l_t \, \Delta S_t}{1 - \frac{W_w}{W} - \frac{w_t}{W} S_t} \qquad (5)$$

where the tail weight per unit area w_t was taken as 2.1 pounds per square foot, and W_w was taken as 2860 pounds. The term ΔS_t represents the change in required S_t due to the tail modification, as determined by equations (1) and (2) on the basis of the original range of permissible center-of-gravity positions.

If the static margin of the airplane with the modified tail is maintained constant by moving the center-of-gravity and wing positions simultaneously, equations (4) and (5) can be written

$$\Delta l_{cg}' = \Delta l_o - 0.132 \, \Delta\frac{S_t}{S} + \Delta l_w'\left(0.68 - 0.0554\frac{S_t}{S}\right) \qquad (6)$$

where the primes for Δl_{cg} and Δl_w indicate that the center-of-gravity and wing positions were moved simultaneously.

The change in control-force gradient in steady turning flight was obtained from the formula

$$F_n = \left(C_{h_{\delta_e}} B + C_{h_{\alpha_t}} D\right) q_t K_e \bar{c}_e^{\,2} b_e \qquad (7)$$

where

$$B = \frac{Wx}{qSC_{m_{\delta_e}}} - \frac{28.6 \rho g C_{m_{\alpha_t}} c_w \left(l_t - l_o + x\right)}{q_t C_{m_{\delta_e}}} \qquad (8)$$

and

$$D = \frac{W\left(1 - \frac{d\epsilon}{d\alpha}\right)}{Sqa} + \frac{28.6\rho g c_w\left(l_t - l_o + x\right)}{q_t} \tag{9}$$

In equations (7) to (9),

$$C_{m_{\delta_e}} = \frac{-q_t S_t \tau a_t\left(l_t - l_o + x\right)}{qS} + \frac{dc_{m_t}}{d\delta_e} \tag{10}$$

where $dc_{m_t}/d\delta_e$ is the contribution to C_m per unit change in δ_e and results from the tail pitching moment about its own quarter-chord point. This term usually contributes a small amount to the value of $C_{m_{\delta_e}}$. In the case of the all-movable tail

$$\frac{dc_{m_t}}{d\delta_e} = \frac{E'\left(\frac{\partial c_m}{\partial \delta f_t}\right)_{C_{L_t}} \frac{\delta f_t}{\delta_e} q_t \bar{c}_t^{\,2} b_e}{qSc_w} \tag{11}$$

where E' is a function of the span and location of the tab and of the tail taper ratio. Values for E' are given in figure 7 of reference 6. In equation (8),

$$C_{m_{\alpha_t}} = \frac{-q_t S_t a_t\left(l_t - l_o + x\right)}{qS} \tag{12}$$

Values for $C_{h_{\delta_e}}$, $C_{h_{\alpha_t}}$, and S_t that were used to determine F_n are discussed in the present paper in the section entitled "Longitudinal Control Characteristics."

The effect on the static longitudinal stability of freeing the elevator control was obtained from the formula

$$\Delta l_{o_F} = \frac{C_{m_{\delta_e}} C_{h_{\alpha_t}}\left(1 - \frac{d\epsilon}{d\alpha}\right)}{aC_{h_{\delta_e}}} \tag{13}$$

where Δl_{o_F} is the shift in the neutral-point position that results from freeing the elevator control. In equation (13) Δl_{o_f} is assumed to be negligible in comparison with the term $l_t - l_o + x$. The expression

$$\frac{-C_{h_{\alpha_t}}\left(1 - \frac{d\epsilon}{d\alpha}\right)}{C_{h_{\delta_e}}}$$

in equation (13) represents the change in floating angle of the elevator per unit change in α.

The control force for the landing condition at the minimum speed with the center of gravity in the most forward position was obtained from the formula

$$F_L = \left[C_{h_{\delta_e}}\delta_{e_{max}} + C_{h_{\alpha_t}}\left(\alpha_t' - \epsilon' + i_{t_{max}}\right)\right] q_t K_e \bar{c}_e{}^2 b_e \quad (14)$$

where α_t' is the geometric angle of attack of the tail that corresponds to the minimum landing speed corrected for ground effect as measured with the stabilizer in the neutral position.

The effects of a partial-wing stall on the control-force gradient in a dive recovery for the three horizontal tails were compared by considering the changes due to the stall in the position of the center of pressure of the wing lift, in the slope of the lift curve of the wing, and in the downwash angle at the tail. In this comparison the effect of the wing stall on factors other than the wing and tail were neglected.

The change in the control-force gradient due to the partial stall in a dive recovery was obtained by means of the formula

$$\left(\Delta F_n\right)_{st} = \frac{W q_t K_e \bar{c}_e{}^2 b_e}{S q}\left\{\frac{\left(\Delta l_o\right)_{st} C_{h_{\delta_e}}}{C_{m_{\delta_e}}} \left[\frac{1 - \left(\frac{d\epsilon}{d\alpha}\right)_{st}}{a_{st}} - \frac{1 - \frac{d\epsilon}{d\alpha}}{a}\right] C_{h_{\alpha_t}}\right\} \quad (15)$$

where a_{st} is the slope of the lift-coefficient curve for the airplane during the wing stall and

$$a_{st} = a_{w_{st}} + \frac{a_t q_t S_t \left[1 - \left(\frac{d\epsilon}{d\alpha}\right)_{st}\right]}{qS}$$

Also $\left(\Delta l_o\right)_{st}$ is the shift in the neutral-point position due to the wing stall and, from equation (1),

$$\left(\Delta l_o\right)_{st} = \frac{K l_t \left[1 - \left(\frac{d\epsilon}{d\alpha}\right)_{st}\right] + \frac{a_{w_{st}}}{a_w} \Delta d_{st}}{\frac{a_{w_{st}}}{a_w} + K\left[1 - \left(\frac{d\epsilon}{d\alpha}\right)_{st}\right]} - \frac{K l_t \left(1 - \frac{d\epsilon}{d\alpha}\right)}{1 + K\left(1 - \frac{d\epsilon}{d\alpha}\right)} \qquad (16)$$

where

$$K = \frac{a_t q_t S_t}{a_w q S}$$

The quantitative results presented in the comparison of the effect of the wing stall on the control-force gradient in a dive recovery were obtained for a partial-wing stall for which it was assumed, for convenience, that

$$\left(\frac{d\epsilon}{d\alpha}\right)_{st} = \frac{a_{w_{st}}}{a_w} \frac{d\epsilon}{d\alpha}$$

and

$$\Delta d_{st} = 0.10\left(1 - \frac{a_{w_{st}}}{a_w}\right)$$

On the basis of these assumptions, equations (15) and (16) become, respectively,

$$\left(\Delta F_n\right)_{st} = \frac{W q_t K_e \bar{c}_e^{\,2} b_e}{qS} \left[\frac{\left(\Delta l_o\right)_{st} C_{h_{\delta_e}}}{C_{m_{\delta_e}}} + \left(\frac{1}{a_{st}} - \frac{1}{a}\right) C_{h_{\alpha_t}}\right] \qquad (17)$$

$$\left(\Delta l_o\right)_{st} = \frac{K l_t \left(1 - \frac{a_{w_{st}}}{a_w} \frac{d\epsilon}{d\alpha}\right) + 0.10 \frac{a_{w_{st}}}{a_w}\left(1 - \frac{a_{w_{st}}}{a_w}\right)}{\frac{a_{w_{st}}}{a_w} + K\left(1 - \frac{a_{w_{st}}}{a_w} \frac{d\epsilon}{d\alpha}\right)} - \frac{K l_t \left(1 - \frac{d\epsilon}{d\alpha}\right)}{1 + K\left(1 - \frac{d\epsilon}{d\alpha}\right)} \qquad (18)$$

RESULTS AND DISCUSSION

Range of Permissible Center-of-Gravity Positions

The rearward and forward boundaries for the permissible range of center-of-gravity positions for the fixed-stabilizer, adjustable-stabilizer, and all-movable horizontal tails are shown in figure 2. The results are shown for values of S_t/S ranging to 0.30. The limiting rearward center-of-gravity position in figure 2 is determined by the requirement for static longitudinal stability in the cruising condition with elevator fixed. This boundary was obtained by solving equation (1) for l_o with specified values of S_t/S. It will be noted from equation (1) that the parameters which affect this boundary generally do not change with the type of horizontal tail. This boundary will be affected, however, by a change in the tail aspect ratio because the term a_t in equation (1) is a function of the tail aspect ratio. Figure 2 indicates that for $\frac{S_t}{S} = 0.175$, which corresponds to the horizontal-tail area of the subject airplane, an increase in the tail aspect ratio from 4.24 to 5.82 increases the static margin by $0.026c_w$.

The forward boundary for the permissible range of center-of-gravity position given in figure 2 is determined by the requirement for adequate control in the critical landing condition. This boundary was obtained by solving equation (2) for l_{cg} for specified values of S_t/S. Figure 2 shows that the boundary for adequate control in the critical landing condition will be shifted considerably forward by replacing the fixed-stabilizer tail with either the adjustable-stabilizer or the all-movable tail. For $\frac{S_t}{S} = 0.155$, the forward boundaries for the adjustable-stabilizer and all-movable tails are $0.18c_w$ and $0.21c_w$, respectively, ahead of that for the fixed-stabilizer tail $(A_t = 5.82)$. Figure 2 shows that in the case of the fixed-stabilizer tail, the effect of aspect ratio on the forward center-of-gravity boundary is small.

The large forward extension of the range of permissible center-of-gravity positions, which results from the use of the adjustable-stabilizer and all-movable tails, is caused by the large increase in C_{L_t}' that can be obtained with these types of horizontal tail as compared with the fixed-stabilizer tail. The calculated value for C_{L_t}' for the fixed-stabilizer tail was -0.029 as compared with -1.05 and -1.25 for the adjustable-stabilizer and all-movable tails, respectively. The numerically larger value for C_{L_t}' obtained with the adjustable-stabilizer tail is due to the influence of the term $i_{t_{max}}$ in equation (3), and for the all-movable tail, the numerically larger value for C_{L_t}' is due to the term τ in equation (3). (See table II.)

The results shown in figure 2 indicate that as compared with the fixed-stabilizer tail of $A_t = 5.82$, the adjustable-stabilizer and all-movable tails permit a reduction in horizontal-tail area of about 40 percent for a given center-of-gravity range. In the case of the fixed-stabilizer tail, the increase in aspect ratio from 4.24 to 5.82 permits a reduction in horizontal-tail area that varies from about 10 to 12.5 percent.

In connection with the comparison shown in figure 2, it should be noted that the tail area required to provide adequate control in the critical landing condition will depend to a significant extent on the conditions specified in regard to limiting the maximum angular travel of the various control surfaces. Thus, in the case of the adjustable-stabilizer tail, the criterion for the maximum stabilizer deflection is likely to be based on the placarded speed for the airplane with flaps down. In this connection, it is noted in reference 9 that longitudinal instability has occurred on several airplanes at small wing angles of attack with flaps down. This instability appears to be caused by stalling of the tail surface due to the comparatively large negative incidence of the tail associated with a small wing angle of attack and a large downwash angle with the flaps deflected. On this basis, if the placarded speed is taken at a value greater than 120 percent of the minimum speed, with suitable allowance for limiting the stabilizer deflection to avert tail stalling, the results indicated in figure 2 for the adjustable stabilizer would be unduly optimistic. Similarly, the results shown in figure 2 for the all-movable tail would be optimistic if the maximum control deflection were so limited that the incidence of the tail in the critical landing condition is a few degrees below the negative stalling angle. For example, the maximum angular travel of the all-movable tail might be limited by the condition that in a wave-off, the sudden application of power should not increase the downwash to the extent of stalling the tail. On this basis, if it were specified for the all-movable tail that its maximum incidence in the critical three-point landing condition should not exceed a value of 2° below its negative stalling angle, then the boundary for adequate control in the landing condition shown in figure 2 would be shifted rearward by a value of the order of $0.21c_w\frac{S_t}{S}$, or about $0.0325c_w$ when $\frac{S_t}{S} = 0.155$.

Static Margin

Figure 2 indicates that a reduction in horizontal-tail area results in a forward shift of the neutral point. Consequently, in order to maintain an equal static margin in conjunction with a reduced horizontal-tail area, the center of gravity should normally be moved ahead a distance equal to the forward shift of the neutral point. In the preliminary stages of design, the required center-of-gravity shift may be accomplished by moving the engine forward. An alternative method for obtaining an equal static margin in conjunction with a reduction in horizontal-tail area is to move the neutral point back by an appropriate rearward movement of the wing.

Figure 3 is given in order to indicate for the airplane the movements of the center-of-gravity or wing position that are required with the reductions in horizontal-tail area associated with various types of tails in order to maintain a specified static margin. The areas for the modified tail designs are based on the condition that they give a range of permissible center-of-gravity positions equal to that obtained with the fixed-stabilizer tail $(A_t = 5.82)$. The respective tail areas were obtained from figure 2, and are shown in figure 3(a). The movements of the center-of-gravity Δl_{cg} or wing position Δl_w required with the fixed-stabilizer $(A_t = 4.24)$, adjustable-stabilizer, and all-movable tails are shown in figure 3(b). The results for Δl_{cg} and Δl_w indicated in figure 3(b) were obtained by means of equations (4) and (5), respectively. The shift of the neutral-point position Δl_o for use in equations (4) and (5), which results from the change in S_t/S associated with the modified tail, was determined from figure 2.

In figure 3(b) the values of Δl_{cg} and Δl_w refer to the case in which either the center-of-gravity or the wing movement is made independent of the other. The required movements of the center-of-gravity and wing positions for the case of a simultaneous movement may be obtained by means of the data of figure 3 on the basis of equation (6).

Figure 4 shows a plan view of the subject airplane with a fixed-stabilizer tail and with an all-movable horizontal tail of reduced area. The all-movable tail with reduced area provides the same range of permissible center-of-gravity positions as the fixed-stabilizer tail, and the rearward movement of the wing of 0.72 foot indicated in figure 4, maintains the original static margin. If the center of gravity of the airplane with the all-movable tail were moved forward 0.265 foot, the original static margin could be maintained with a rearward movement of the wing of 0.332 foot.

Longitudinal Control Characteristics

With a given horizontal tail, the control-force characteristics may be varied over a wide range by adjusting the values for the hinge-moment parameters $C_{h_{\delta_e}}$ and $C_{h_{\alpha_t}}$. The present analysis of the control-force characteristics is given, however, in order to compare some typical values for $C_{h_{\delta_e}}$ and $C_{h_{\alpha_t}}$, which are required with the various horizontal tails to provide comparable control-force characteristics with an equal permissible variation in the center-of-gravity position. The analysis also compares the effect of a partial-wing stall on the control-force gradient in a dive recovery.

The horizontal tails are compared on the basis of the original range of permissible center-of-gravity positions of the subject airplane of $0.103c_w$. The respective areas for the fixed-stabilizer tails (A_t = 4.24 and 5.82) and for the adjustable-stabilizer and all-movable tails are then 41.4, 36.6, 22.6, and 20.8 square feet.

[redacted]

The results of the calculations for the hinge-moment parameters $C_{h_{\delta_e}}$ and $C_{h_{\alpha_t}}$, and for F_n, $0.01\ \partial F_n/\partial x$, Δl_{o_F}, and F_L are given in table III. The data for F_n and $0.01\ \partial F_n/\partial x$ were obtained by use of equations (7) to (9) for a static margin x equal to $0.05c_w$ and for an altitude of 3000 feet. The results in table III are given for the fixed-stabilizer tail $(A_t = 4.24)$ for values of $C_{h_{\delta_e}}$ and $C_{h_{\alpha_t}}$ that were determined on the basis of unpublished flight tests of the airplane. The results are also presented for all the tails on the basis of the values of $C_{h_{\delta_e}}$ and $C_{h_{\alpha_t}}$ required to provide a control-force gradient F_n equal to 3.27 pounds per g and a value of $0.01\ \partial F_n/\partial x$ equal to 0.52 pounds per g per percent change in x. The estimated control balance required with the tails in order to obtain the foregoing values of $C_{h_{\delta_e}}$ and $C_{h_{\alpha_t}}$ are also compared in table III. The control-balance requirements for the fixed-stabilizer and adjustable-stabilizer tails were estimated on the basis of the typical hinge-moment data given in figure 2 of reference 3; whereas the balance requirements for the all-movable tail were obtained by use of the formulas given in the appendix of the present report.

The results given in table III indicate that in order to obtain values of F_n equal to 3.27 and values of $0.01\ \partial F_n/\partial x$ equal to 0.52 with a static margin of $0.05c_w$ either of the fixed-stabilizer tails would require appreciable reductions in the magnitudes of $C_{h_{\delta_e}}$ and $C_{h_{\alpha_t}}$ by use of balancing devices. These data also indicate that if the aspect ratio of the fixed-stabilizer tail is increased from 4.24 to 5.32, the required control balance for $C_{h_{\delta_e}}$ would be reduced by about 12 percent. For the adjustable-stabilizer tail, table III shows that in order to obtain the foregoing values for F_n and $0.10\ \partial F_n/\partial x$, a very small degree of balance would be required to obtain the indicated value for $C_{h_{\delta_e}}$; whereas appreciable balance would be required to obtain the value indicated for $C_{h_{\alpha_t}}$. For the all-movable tail, the formulasgiven in the appendix of the present paper indicate that the value for $C_{h_{\delta_e}}$ shown in table III could be obtained by use of a tab, which covers the middle part of the tail semispan, and has a linkage ratio δ_{f_t}/δ_e of 0.6, a chord equal to $0.08c_e$, and a span of $0.25b_e$; whereas the tabulated value of $C_{h_{\alpha_t}}$ of zero could be obtained by locating the pivot of the main surface at its aerodynamic center.

The data given in table III for the effect of freeing the elevator control Δl_{o_F} and for the control forces required in the critical landing condition F_L were obtained by use of equations (13) and (14), respectively. The results indicate that the values of Δl_{o_F} are small for all the tails. The control forces required in the critical landing condition are approximately the same for the fixed-stabilizer and the all-movable tails but are lower for the adjustable-stabilizer tail.

Effect of Partial-Wing Stall on Control-Force Gradient in a Dive Recovery

Under certain flight conditions, such as in a high-speed dive recovery, the wing is apt to become partially stalled and the lack of adequate controllability of the resulting large diving moment may be very serious. A consideration of factors associated with the wing stall, such as the reductions in the slope of the wing lift curve and in the downwash angle at the tail, indicates that the diving moment that results from a wing stall will be influenced to an important extent by the horizontal tail area. The diving moment contributed by the horizontal tail as a result of the wing stall is assumed to increase directly as the product $C_{m_{\alpha_t}}\left(\Delta\alpha_{t_{st}} + \Delta\epsilon_{st}\right)$ where $\Delta\alpha_{t_{st}} + \Delta\epsilon_{st}$ is the increase in angle of attack at the tail due to the wing stall. The derivative $C_{m_{\alpha_t}}$, however, numerically increases directly as the horizontal-tail area; therefore for a given increase in the angle of attack at the tail, the resulting diving moment will increase directly as the horizontal-tail area. The moment about the airplane center of gravity that results from the reduction in the wing lift-curve slope in the stall is also affected by the horizontal-tail area. In a given airplane, an increase in the horizontal-tail area results in a rearward movement of the neutral point, and for a specified static margin this movement of the neutral point in turn involves a corresponding rearward movement of the center of gravity. For a specified static margin, the relation between the positions of the wing and the center of gravity is therefore such that the reduction in the wing lift-curve slope associated with the stall tends to reduce the stalling moment or to increase the diving moment as the horizontal-tail area is increased.

On the basis of the foregoing discussion, it appears that in a high-speed dive recovery in which the wing may become partially stalled, the small horizontal-tail areas associated with the adjustable-stabilizer and all-movable tails should, in general, significantly improve the longitudinal control characteristics over those obtained with the conventional fixed-stabilizer horizontal tail. Figure 5 is presented in order to give a quantitative comparison of the effect of a partial-wing stall on the control-force gradient in a dive recovery as obtained with the conventional fixed-stabilizer, adjustable-stabilizer, and all-movable horizontal tails. The area of each of the horizontal tails is given and is based on a range of permissible center-of-gravity positions of $0.103c_w$ as determined from figure 2 for the original horizontal tail of the airplane.

Figure 5 presents the results of the computations for the increase in control-force gradient due to a partial-wing stall in a dive pull-out made at constant speed. The results for $(\Delta F_n)_{st}$ in this figure were calculated by means of equations (17) and (18) and are shown for a range of values of $a_{w_{st}}/a_w$ from 0.6 to 1.0. These values of $a_{w_{st}}/a_w$ may occur in the case of a high-speed pull-out in which the thicker sections near the root and those close to the wing-fuselage juncture tend to stall due to critical compressibility effects. These data for $(\Delta F_n)_{st}$ for the tails are based on the same values for $C_{h_{\delta_e}}$ and $C_{h_{\alpha_t}}$ that are given in table III.

The results in figure 5 indicate that the wing stall causes a greater increase in the control-force gradient with the fixed-stabilizer tail than with the adjustable-stabilizer and all-movable tails. Thus for $a_{w_{st}}/a_w$ equal to 0.8, the values for $(\Delta F_n)_{st}$ for the adjustable-stabilizer and all-movable tails are, respectively, 21.8 percent and 26 percent smaller than the value obtained with the modified fixed-stabilizer tails. The magnitude of these reductions in $(\Delta F_n)_{st}$ obtained with the adjustable-stabilizer and all-movable tails as compared with the fixed-stabilizer tail also become greater as the wing becomes more stalled. Figure 5 indicates that for the fixed-stabilizer tail the increase in aspect ratio from 4.24 to 5.82 with an appropriate reduction in tail area has no effect on $(\Delta F_n)_{st}$.

CONCLUSIONS

An analysis made in order to compare a conventional fixed-stabilizer, an adjustable-stabilizer, and an all-movable horizontal tail indicated the following conclusions:

1. The all-movable and adjustable-stabilizer horizontal tails have a large advantage over the conventional fixed-stabilizer tail in regard to tail-area requirements. For a specified range of permissible center-of-gravity positions, the all-movable and adjustable-stabilizer tails permit reductions in tail area of approximately 40 percent, as compared with the fixed-stabilizer tail.

2. A specified static margin can be maintained with large reductions in horizontal-tail area by adjustments in the center-of-gravity or wing positions, which are feasible in the preliminary stages of design.

3. The comparison of the longitudinal-control characteristics obtained with the horizontal tails, which was made on the basis of tail areas that correspond to the same range of permissible center-of-gravity positions and on the basis of similar dive-recovery characteristics for conditions below the wing stall, indicated the following:

(a) For the adjustable-stabilizer tail, the required value for the rate of change of hinge-moment coefficient with elevator deflection can be obtained with appreciably smaller control balance than would be required with the fixed-stabilizer tail.

(b) The control forces required to effect a three-point landing at minimum speed will be smallest with the adjustable-stabilizer tail and will be approximately the same with the fixed-stabilizer and all-movable horizontal tails.

(c) The increase in control-force gradient in a dive recovery, which results from a partial-wing stall, will be significantly smaller with the all-movable and adjustable-stabilizer tails than with the conventional fixed-stabilizer tail.

4. In the case of the fixed-stabilizer tail, an increase in aspect ratio from 4.24 to 5.82 for a specified range of permissible center-of-gravity positions permits a reduction in tail area that varies from approximately 10 to 12.5 percent. This increase in tail aspect ratio with the appropriate reduction in tail area will, in general, have a slightly favorable effect on the longitudinal control characteristics below the wing stall, and will have no effect on the increase in the control-force gradient in a dive recovery due to the stall.

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APPENDIX

ESTIMATION OF HINGE-MOMENT PARAMETERS FOR ALL-MOVABLE TAIL WITH A TAB

An estimation of the hinge-moment parameters $C_{h_{\alpha_t}}$ and $C_{h_{\delta_e}}$ for an all-movable tail with a tab, may be obtained from the following approximate formulas:

$$C_{h_{\alpha_t}} = a_t \frac{p}{c_t} \tag{A1}$$

where p is the distance measured back from the tail aerodynamic center to the pivot of the main surface.

For a full-span tab

$$C_{h_{\delta_e}} = a_t \frac{p}{c_t}\left[1 - \left(\frac{\partial \alpha_t}{\partial \delta_{f_t}}\right)_{c_{l_t}} \frac{\delta_{f_t}}{\delta_e}\right] + \left(\frac{\partial c_{m_t}}{\partial \delta_{f_t}}\right)_{c_{l_t}} \frac{\delta_{f_t}}{\delta_e} \tag{A2}$$

For a partial-span tab

$$C_{h_{\delta_e}} = a_t \frac{p}{c_t} + E'\left[\left(\frac{\partial c_{m_t}}{\partial \delta_{f_t}}\right)_{c_{l_t}} \frac{\delta_{f_t}}{\delta_e} - 0.1J\left(\frac{\partial \alpha_t}{\partial \delta_{f_t}}\right)_{c_{l_t}} \frac{p}{c_t}\right] \tag{A3}$$

where J and E' are functions of the span and location of the tab and of the tail taper ratio. Values for J and E' are given in references 5 and 7, respectively.

If the pivot is located at the aerodynamic center, $C_{h_{\alpha_t}} = 0$ and

$$C_{h_{\delta_e}} = E'\left(\frac{\partial c_{m_t}}{\partial \delta_{f_t}}\right)_{c_{l_t}} \frac{\delta_{f_t}}{\delta_e} \tag{A4}$$

Equations (A1) to (A4) are based on strip theory and neglect a small increment in hinge moment, which is transmitted by the tab to the fuselage instead of to the control column.

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[redacted]

TABLE I - BASIC DATA FOR SUBJECT AIRPLANE

Weight, W (lb)	Wing area, S (sq ft)	Wing span, b (ft)	c_w (ft)	Aspect ratio, A	Taper ratio, r	Flap type	Flap span	$C_{L_{max}}$	a (per deg)	Tail length, l_t (fraction of c_w)	K_e (radian per ft)
8950	236	37	6.64	5.82	2.16	Plain	0.60b	1.72	0.072	2.38	0.57

TABLE II - BASIC AERODYNAMIC AND DESIGN DATA FOR HORIZONTAL TAILS

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$$\left[\frac{d\epsilon}{d\alpha} = 0.4;\ \frac{q_t}{q} = 0.95\right]$$

Horizontal tail	Aspect ratio, A_t	Taper ratio, r_t	c_e/c_t	$\bar{c}_e$ (ft)	$\bar{c}_t$ (ft)	Span, b_t (ft)	$\delta_{e_{max}}$ (deg)	$i_{t_{max}}$ (deg)	a_t (per deg)	τ
Fixed stabilizer	4.24	1.71	0.32	$0.157\sqrt{S_t}$	$0.492\sqrt{S_t}$	$2.06\sqrt{S_t}$	-25	2.0	0.0635	0.59
Fixed stabilizer	5.82	2.16	.32	$.136\sqrt{S_t}$	$.425\sqrt{S_t}$	$2.42\sqrt{S_t}$	-25	2.0	.0720	.59
Adjustable stabilizer	5.82	2.16	.20	$.085\sqrt{S_t}$	$.425\sqrt{S_t}$	$2.42\sqrt{S_t}$	-15	-15.6	.0720	.47
All movable	5.82	2.16	1.00	$.425\sqrt{S_t}$	$.425\sqrt{S_t}$	$2.42\sqrt{S_t}$	-24	0	.0720	[a]1.04

[a]Includes effect of tab.

TABLE III - SUMMARY OF RESULTS FOR AIRPLANE WITH ORIGINAL RANGE
OF PERMISSIBLE CENTER-OF-GRAVITY POSITIONS
OF $0.103c_w$

Horizontal tail	Tail area, S_t (sq ft)	Movement of center of gravity or wing (fraction of c_w)		Longitudinal control characteristics (Altitude, 3000 ft)								
				$C_{h_{\delta_e}}$		$C_{h_{\alpha_t}}$		Wing unstalled				Effect of wing stall
		Δl_{cg}	Δl_w	Value	Estimated balance requirement (percent)	Value	Estimated balance requirement (percent)	F_n for $x = 0.05c_w$ (lb per g)	$0.01\ \partial F_n/\partial x$ (lb per g per percent c_w)	Δl_{oF} (fraction of c_w)	F_L (lb)	$(\Delta F_n)_{st}$ for $a_{w_{st}} = 0.8a_w$ (lb per g)
Fixed stabilizer (original; $A_t = 4.24$)	41.4	0	0	-0.00670	42.5	-0.000539	90.0	7.35	1.21	-0.00950	26.8	10.4
Fixed stabilizer (modified; $A_t = 4.24$)	41.4	0	0	-.00289	75.0	-.000188	96.5	3.27	.52	-.00769	11.6	4.6
Fixed stabilizer ($A_t = 5.82$)	36.6	.006	-.008	-.00392	66.0	-.000256	97.0	3.27	.52	-.00767	11.5	4.6
Adjustable stabilizer	22.6	-.062	.090	-.0104	4.6	-.000190	95.0	3.27	.52	-.00111	3.56	3.6
All movable	20.8	-.070	.102	-.00096	Suitable tab (see text page 22)	0	Pivot located at aerodynamic center of main surface	3.27	.52	0	11.5	3.4

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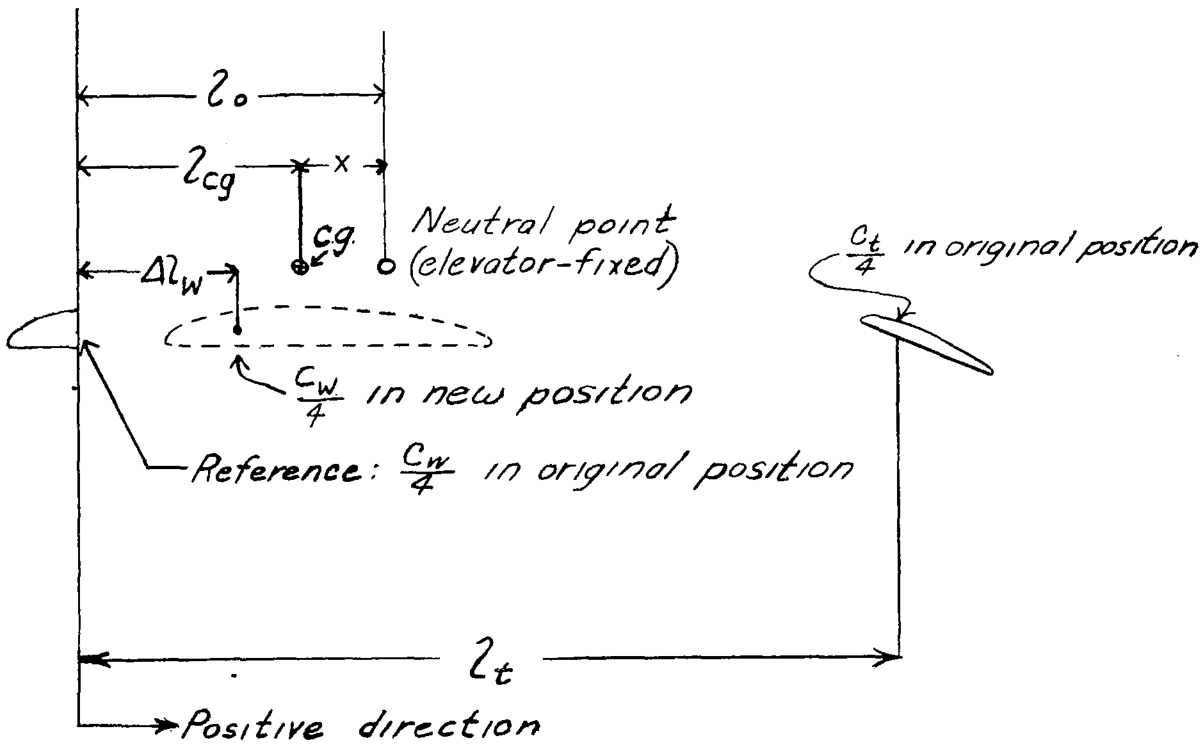

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Figure 1.- Position of various points along longitudinal axis of airplane. Distances measured in fractions of c_w.

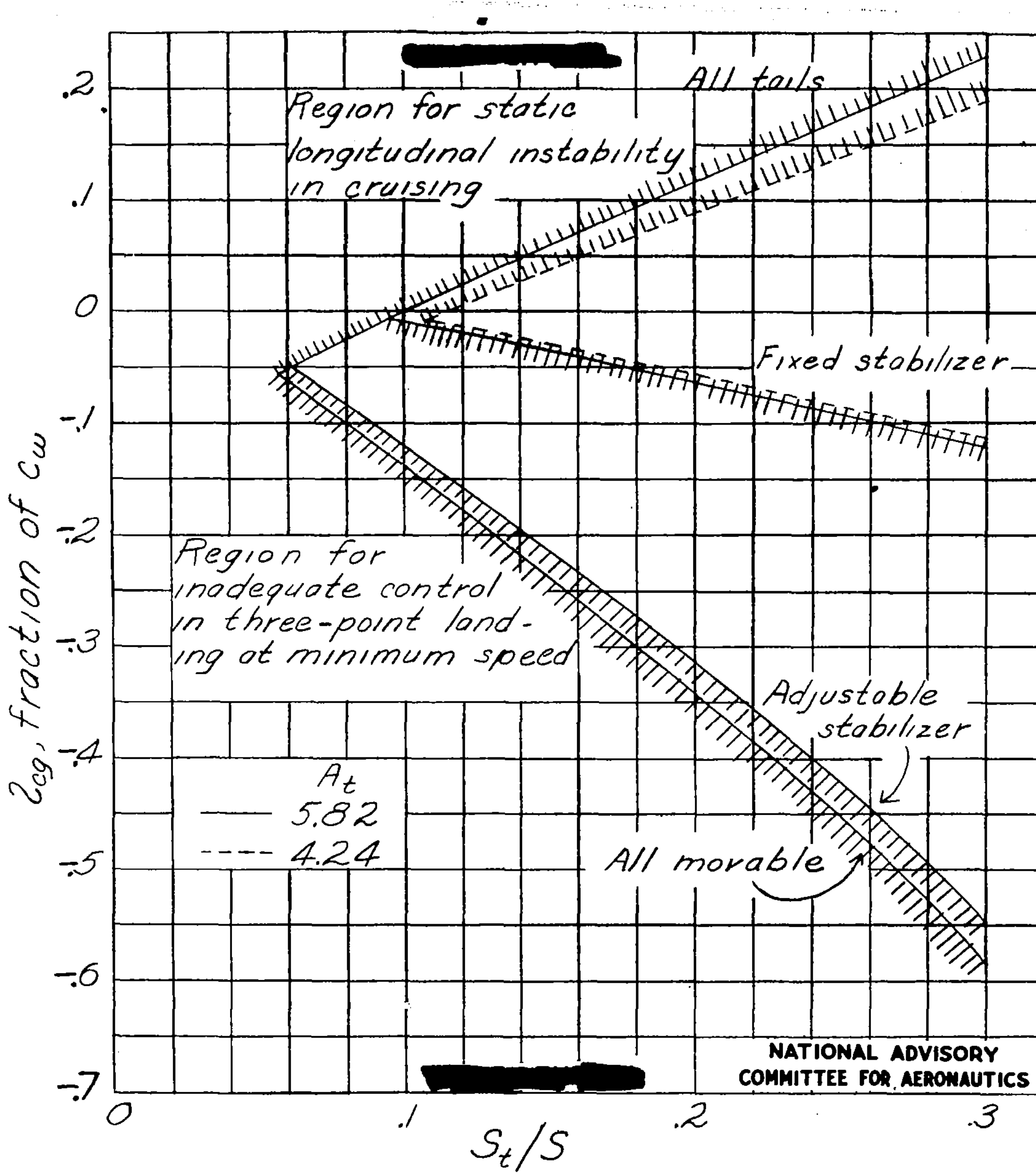

Figure 2.- Variation with horizontal-tail area of permissible center-of-gravity positions for fixed-stabilizer, adjustable-stabilizer, and all-movable horizontal tails.

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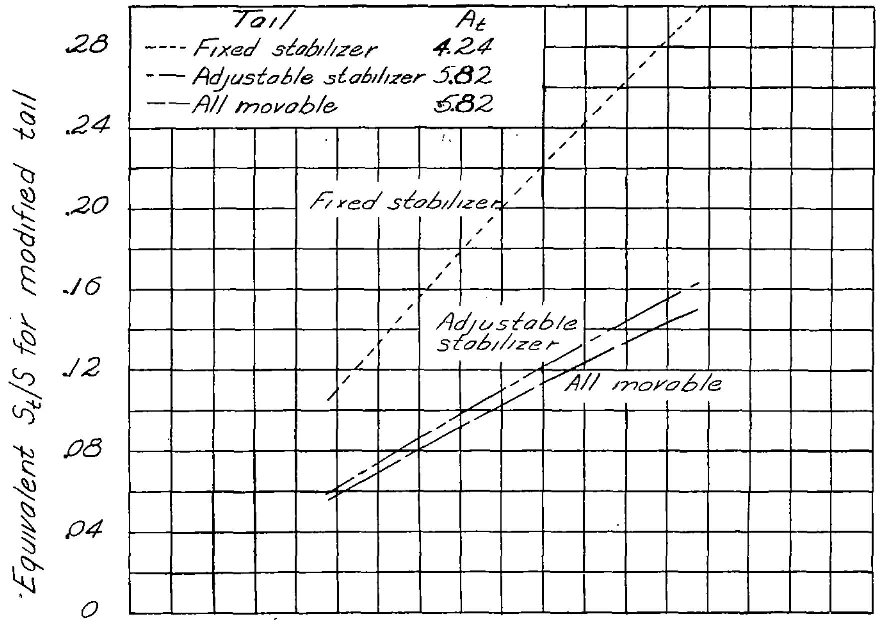
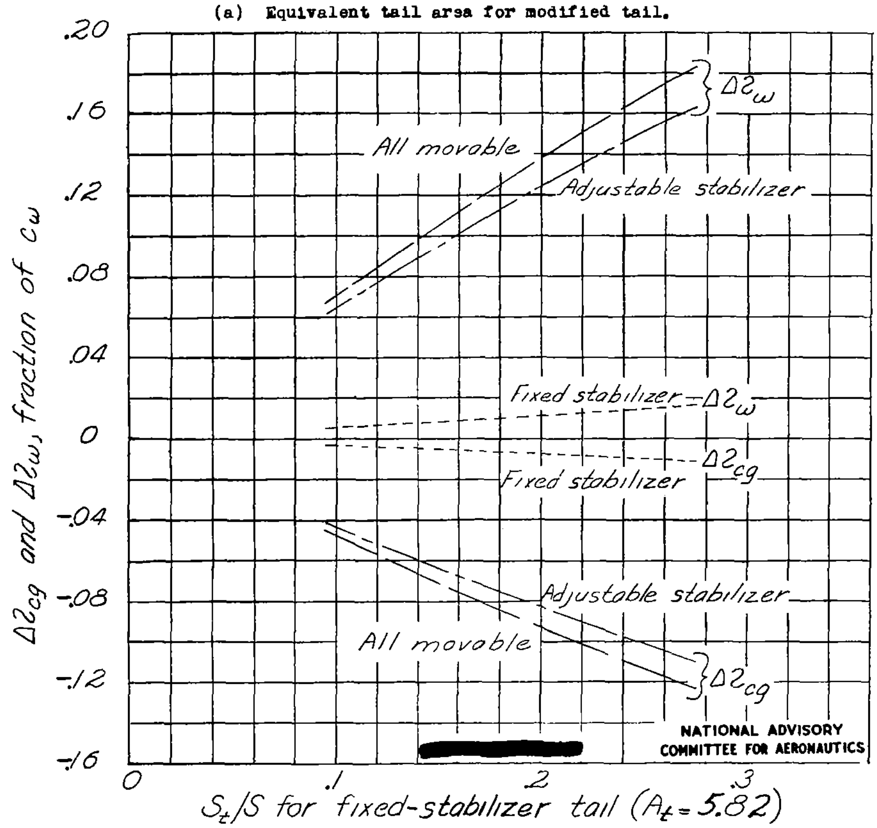


(a) Equivalent tail area for modified tail.



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(b) Required movements of center-of-gravity or wing position.

Figure 3.- Movements of center-of-gravity or wing position required to maintain original static margin with changes in horizontal-tail area associated with three types of tail. Equivalent area of tails in each case gives same permissible range of center-of-gravity position as obtained with fixed-stabilizer tail (A_t = 5.82).

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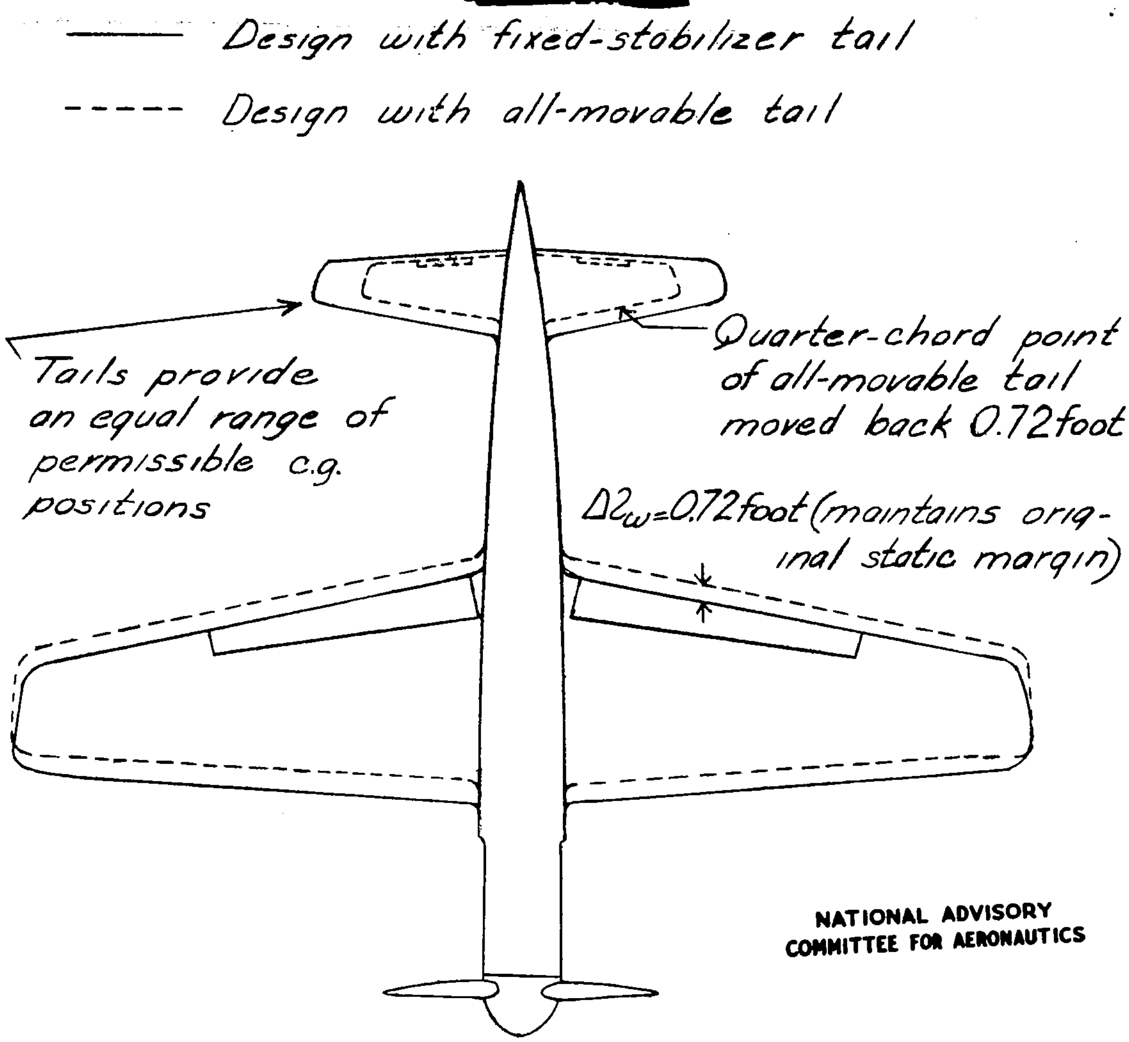

Tail	Tail area, S_t (sq ft)	Tail span, b_t (ft)	Mean tail chord (ft)
Fixed stabilizer	36.6	14.64	2.57
All movable	20.8	11.0	1.89

[redacted]

Figure 4.- Plan view of selected fighter airplane with reduced horizontal-tail area obtained by use of all-movable tail.

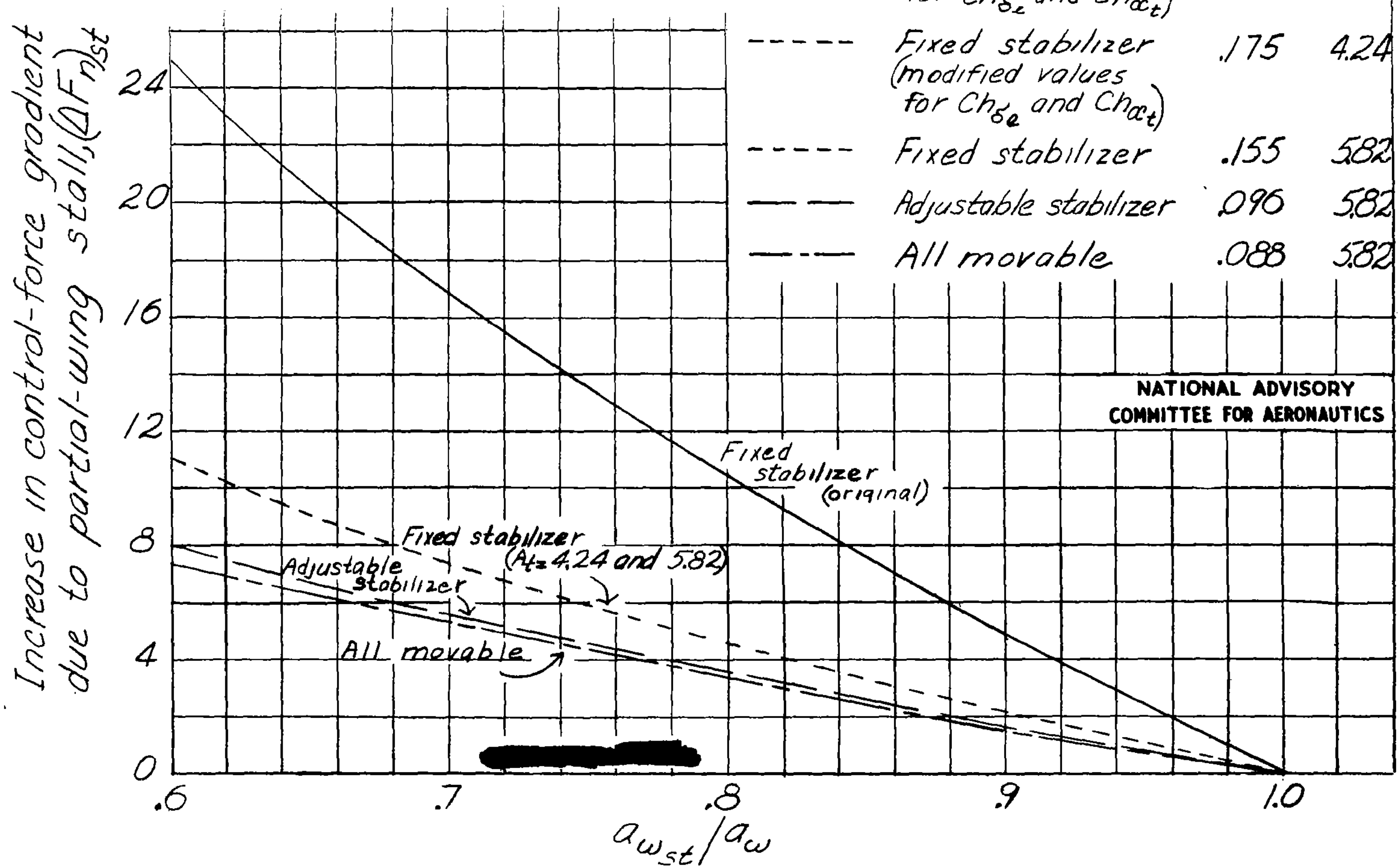

Figure 5.- Comparison of effect of partial-wing stall on control force required in dive recovery for three types of horizontal tail. Permissible range of center-of-gravity positions, $0.103c_w$; $\left(\frac{d\epsilon}{d\alpha}\right)_{st} = \frac{a_{w_{st}}}{a_w}\left(\frac{d\epsilon}{d\alpha}\right)$; $\Delta d_{st} = 0.10\left(1 - \frac{a_{w_{st}}}{a_w}\right)$; altitude, 3000 feet.